

Quadrupole and Multipole Corrector Magnets for LHC and Beyond



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CEA-DSM-DAPNIA-STCM**

VLHC Magnet Workshop
24-26 May 2000

Contents



- **Quadrupole Magnets**
 - LHC Arcs
 - LHC IRs
 - LHC IRs Upgrade
 - TESLA Final Focusing
- **Multipole Corrector Magnets**

Contents

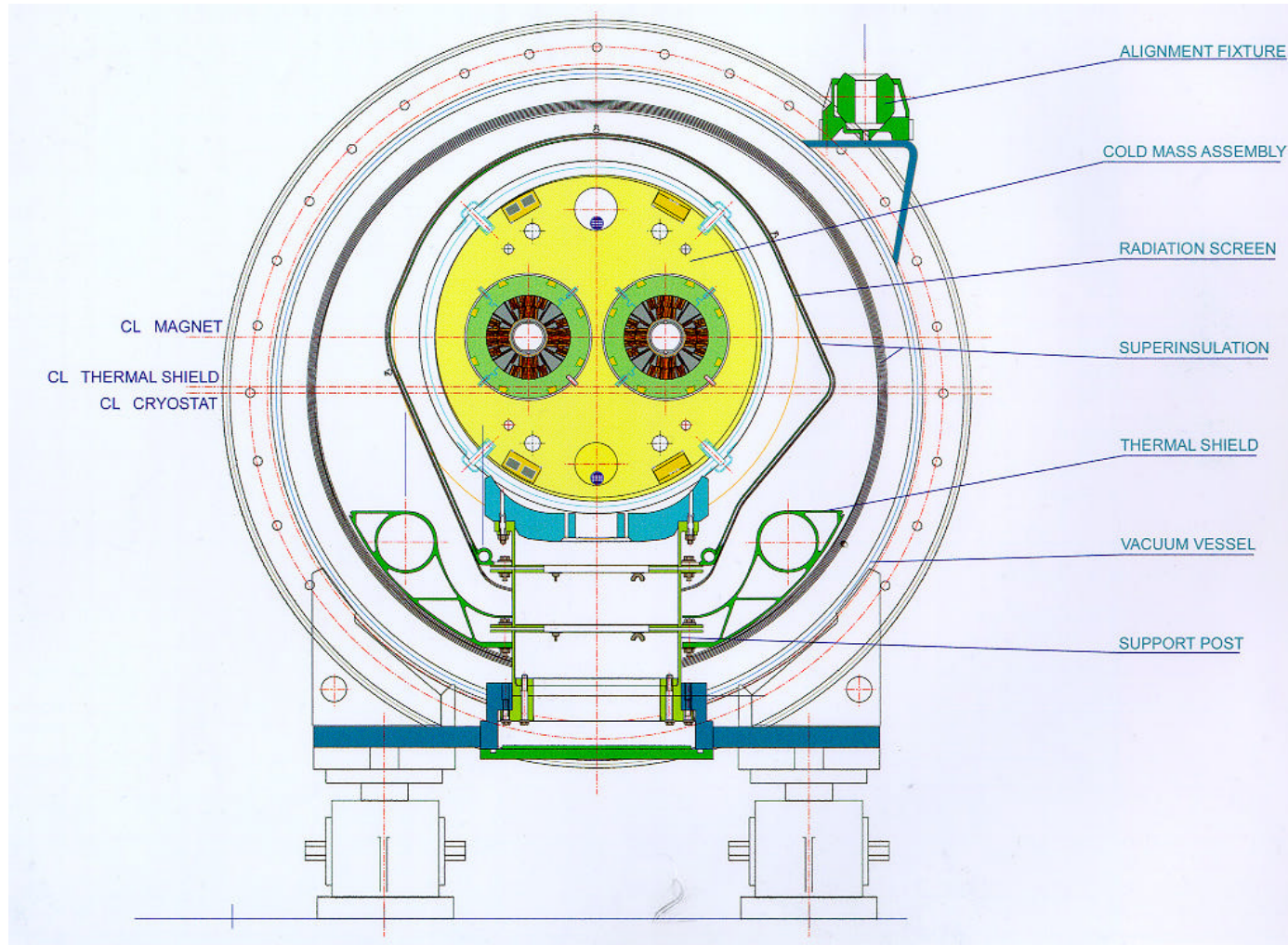


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LHC Arc Quadrupole Magnet Development

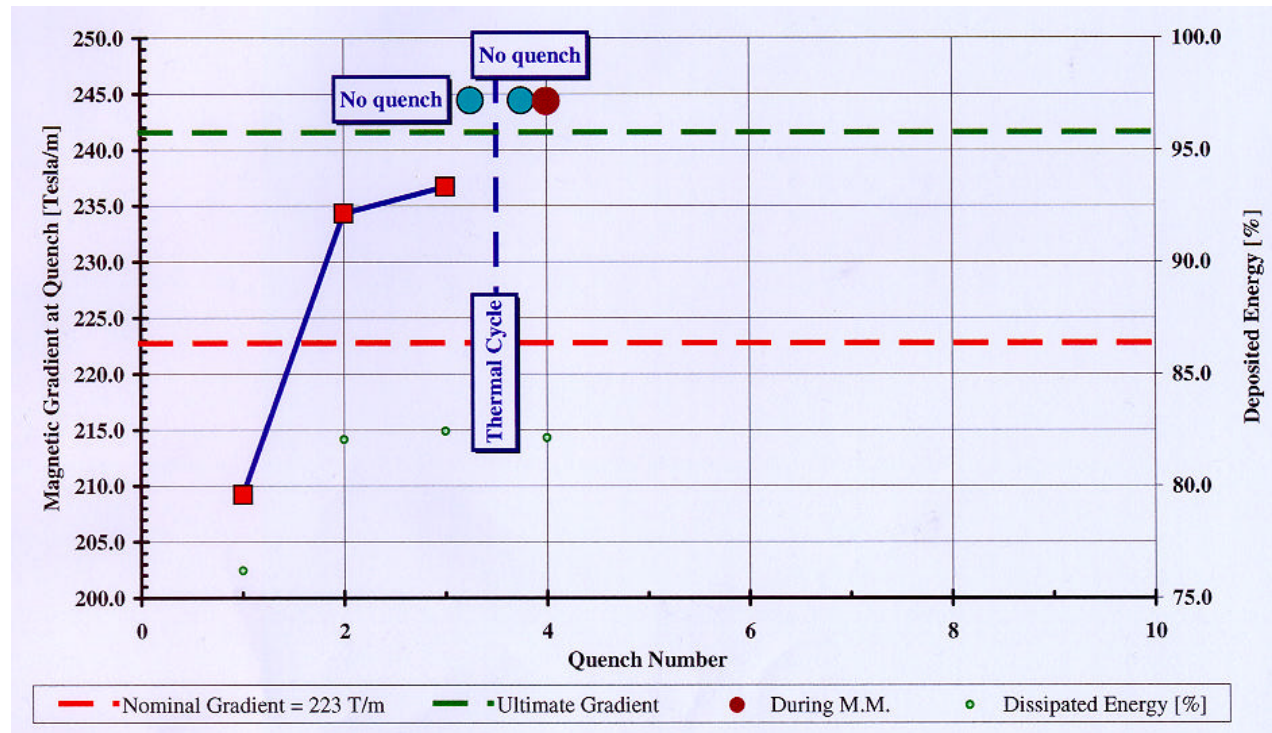
- CEA/Saclay is in charge of developing and following-up the industrialization of the 3-m-long, **56-mm-twin-aperture** quadrupole magnets for the LHC arcs (as part of the 204 man.year special contribution of France to LHC)
- Three full-length prototypes of the final design (with a field gradient of **223 T/m**) have been built at CEA/Saclay
- The design is scaled-up from the HERA and SSC/HEB designs (with a 11 870 A operating current and a **6.85 T** peakfield)

Saclay Design



First Test Results at 1.8 K

- The first prototype was tested at CERN last March, the second one will be tested at CERN in June, and the third one will be tested at CEA/Saclay in September



(Courtesy A. Siemko)

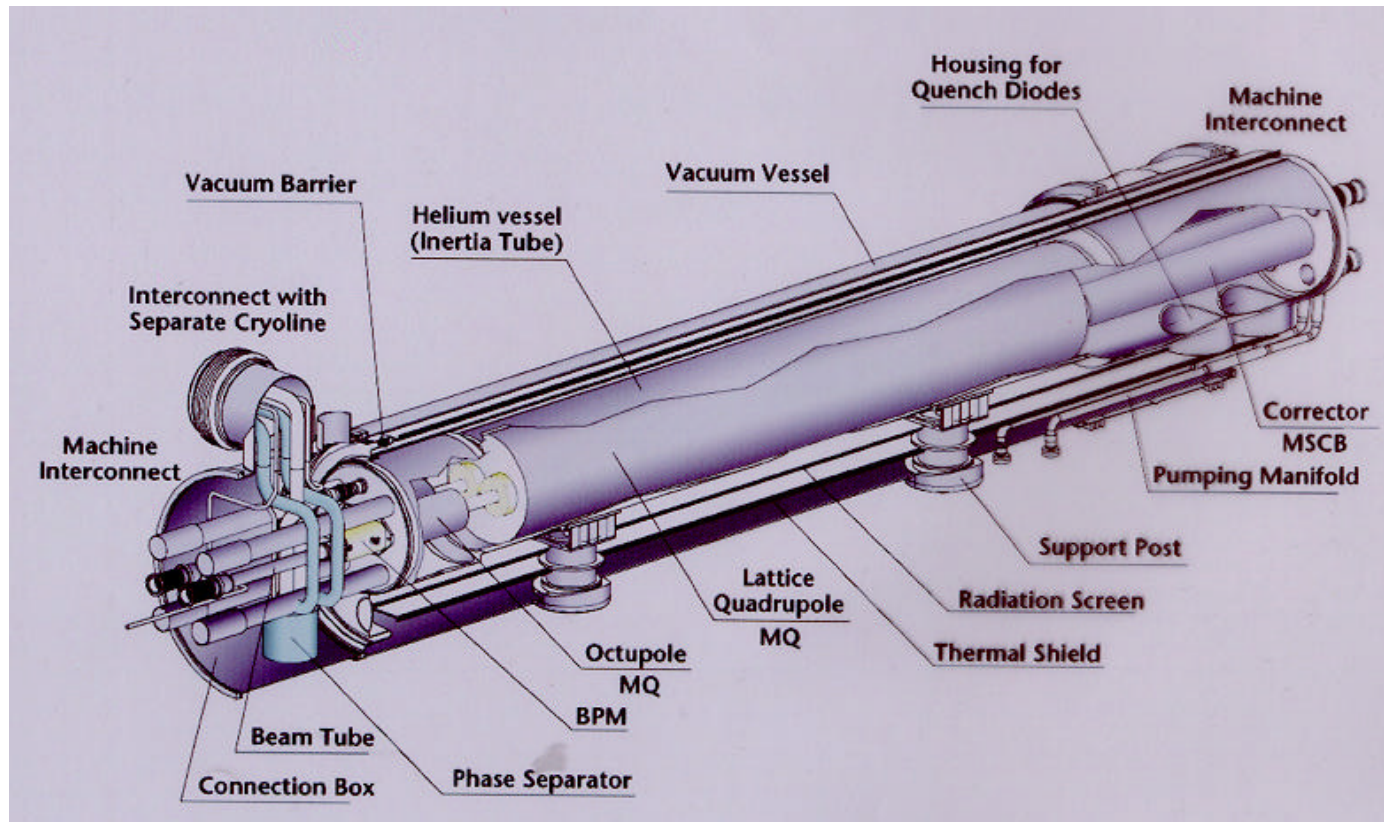
Status of Industrialization



- The contract for the production of ~400 cold masses has been awarded to Accel (Germany) last March
- The first industry-produced cold mass is expected to be delivered to CERN at the end of 2001
- The production is expected to take ~4 years

LHC Short Straight Section

- The LHC arc quadrupole magnet is mounted in a cryostat housing several corrector magnets, a beam position monitor and a cryogenic module



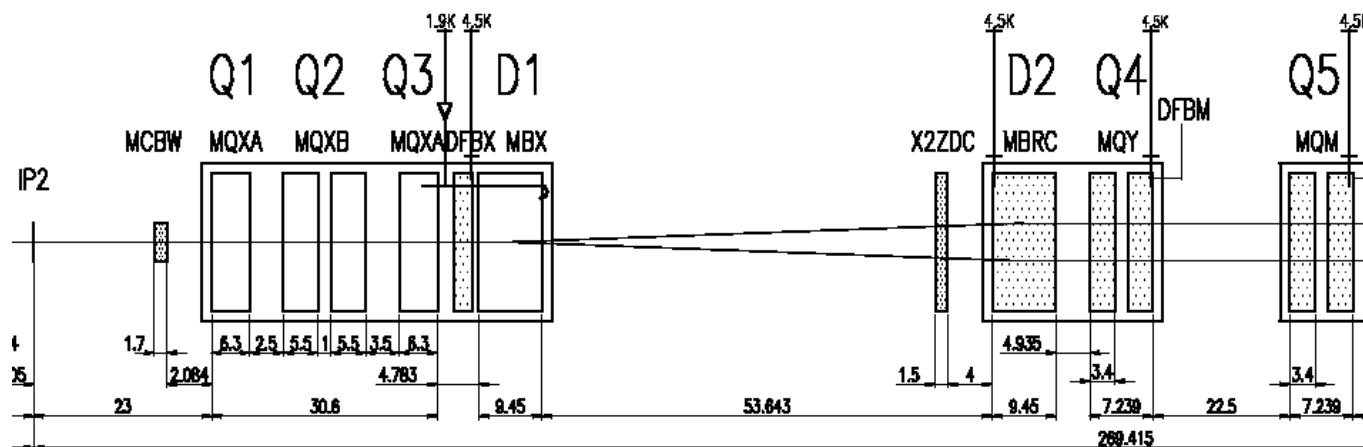
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LHC IR Quadrupole Magnets

- In addition to the arc quadrupole magnets, LHC requires 8 inner triplets of quadrupole magnets to ensure the final focusing of the beams on both sides of the four interaction points



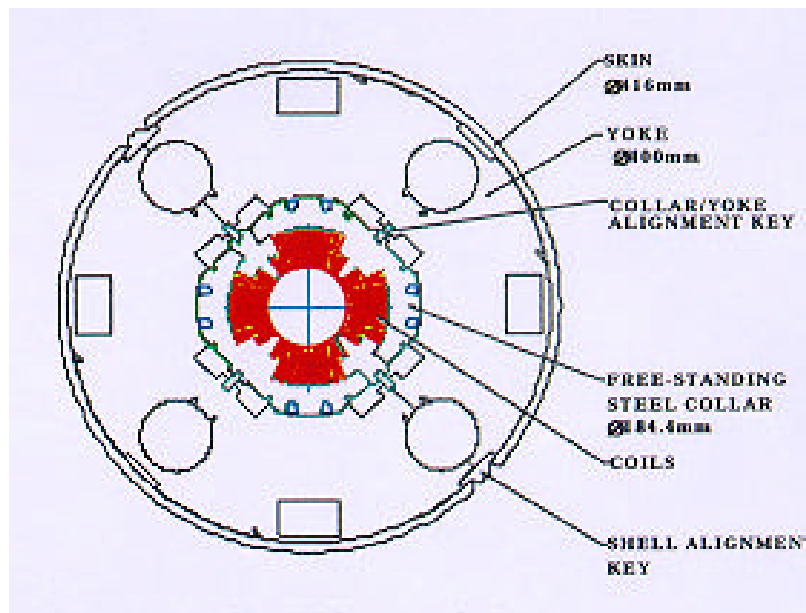
Proposed magnet lattice for the right-hand side
of the #2 interaction point of LHC

LHC IR Quadrupole Magnets (Cont.)

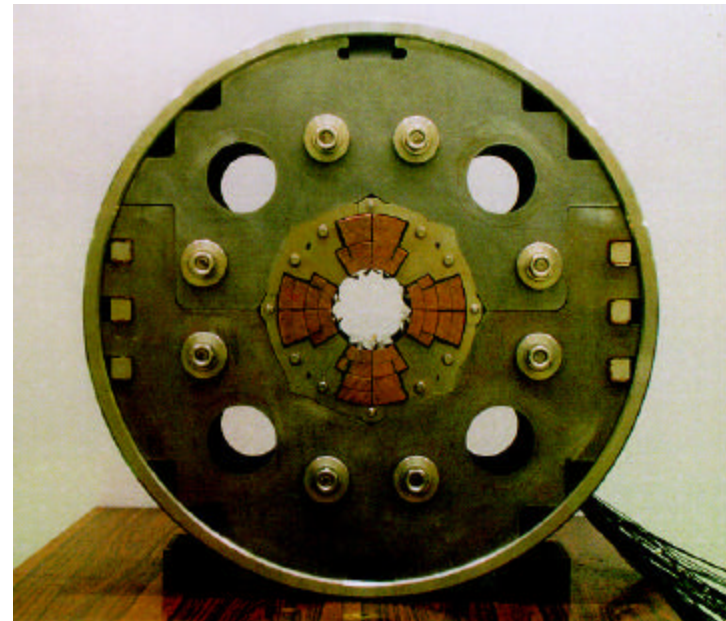
- Each triplet is made up of 4 quadrupole magnets, with lattice designation Q1, Q2a, Q2b and Q3
- The aperture is **70 mm** for all 32 magnets
- The nominal field gradient is **205 T/m** for the magnets located at the high-luminosity IRs and **215 T/m** for the others
- The USA are responsible for providing the Q1 and Q3 cold masses while Japan is responsible for providing the Q2a and Q2b cold masses, as part of special contributions of these two countries to LHC

LHC IR Quadrupole Magnet Designs

- The US magnets are mainly developed at Fermilab, while the Japanese magnets are developed at KEK



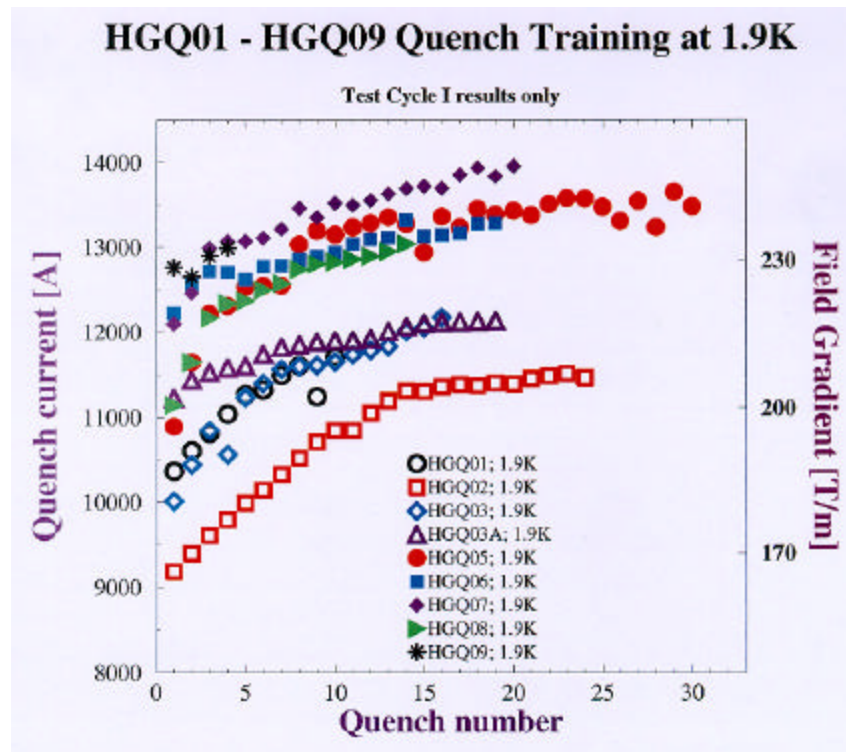
Fermilab Design
12 000 A, 8.30 T @215 T/m
(Courtesy J. Kerby)



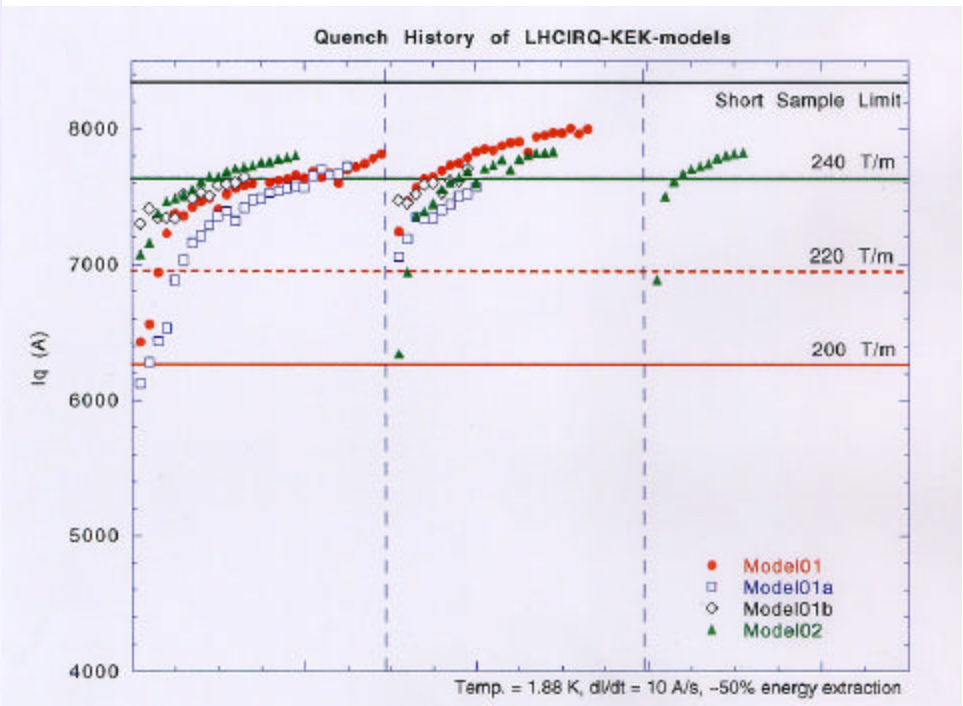
KEK Design
7 149 A, 8.63 T @215 T/m
(Courtesy A. Yamamoto)

Magnet Model Test Results

- Fermilab and KEK have tested a number of short magnet models



Fermilab Model Magnets



KEK Model Magnets

Production of LHC IR Quadrupole Magnets



- Fermilab is building two full-length prototypes and will produce the 16 Q2a and Q2b cold masses in house
- KEK has awarded a contract to Toshiba Corporation to build one full-length prototype and the 16 Q1 and Q3 cold masses (+ 2 spare)

Contents



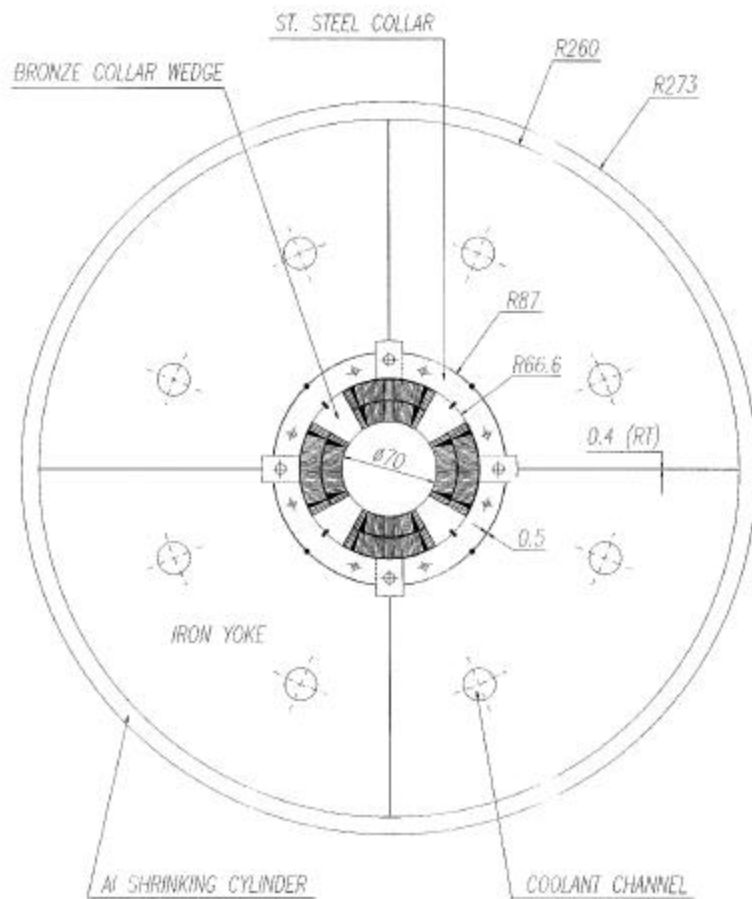
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R&D at INFN/MILAN



- INFN Milan (LASA) has investigated various designs of large-aperture, high-field-gradient quadrupole magnets for a possible upgrade of the LHC Inner Triplets
- and has collaborated with Europa Metalli to develop high- J_c Nb₃Sn wires ([see my other talk at this workshop](#))
- The program is now on hold because of lack of funding

R&D at INFN/MILAN (Cont.)



- Example of conceptual design for a **70-mm-aperture, 300 T/m** quadrupole magnet
- The operating current is 17.9 kA and the peakfield is **11.5 T**
- It requires a high-performance Nb_3Sn wire, with a $J_c(\text{non-Cu})$ of **1800 A/mm²** at 4.2 K and 12 T (to be operated at **1.8 K**)

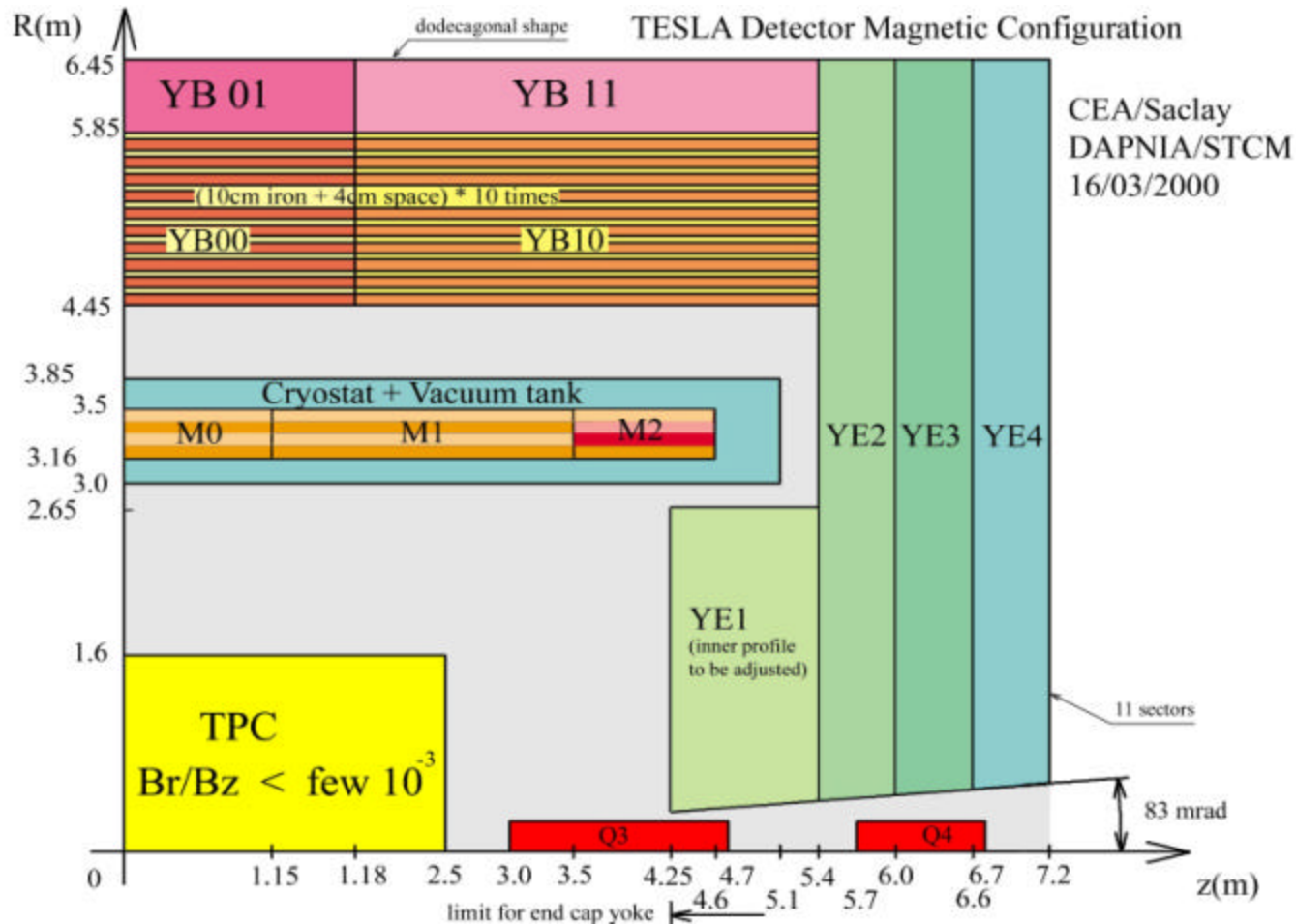
(G. Ambrosio, 1996)

Contents



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Final Focusing of TESLA

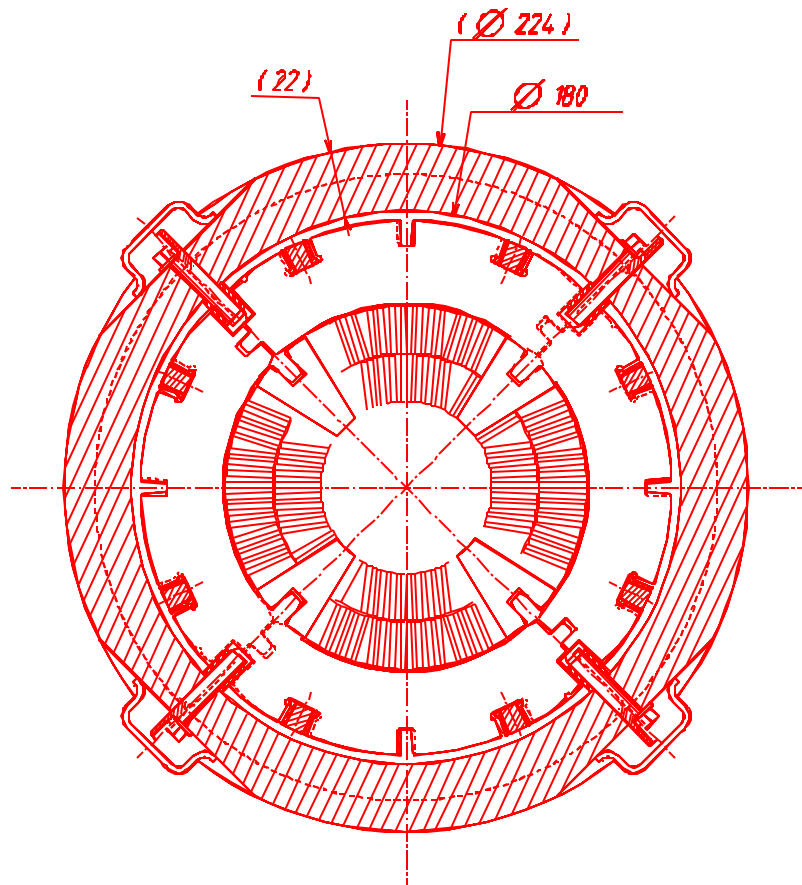


(Courtesy F. Kircher)

Final Focusing of TESLA (Cont.)

- The 4 final focusing quadrupole magnets are modeled after the LHC arc quadrupole magnets (with a single aperture of 56 mm, a field gradient of 250 T/m, and loose specifications on field distortions),
- but two of the magnets are positioned within the detector solenoid and must sustain a 4 T axial field.
- The presence of the background field precludes the use of NbTi and calls for the use of Nb₃Sn.

R&D at CEA/Saclay



(Courtesy J. Thinel)

- CEA/DSM/DAPNIA/STCM has started in 1996 an R&D program aimed at building a Nb₃Sn quadrupole magnet model
- The design relies extensively on the present design for the LHC arc quadrupole magnets (with a single aperture and no iron yoke)
- In this design, **250 T/m** is achieved for a current of 14 065 A, corresponding to a (stand-alone) peakfield (B_{per}) of **7.65 T**

R&D at CEA/Saclay (Cont.)



- A 1-m-long magnet model will be built, using a cable and a wire produced by Alstom, with a $J_c(\text{non-Cu})$ of **750 A/mm²** at 4.2 K and 12 T
(see my other talk at this workshop)
- The model is expected to be tested in March 2003 and should achieve **223 T/m at 4.2 K** (nominal gradient of NbTi, LHC arc quadrupole magnets at 1.9 K)

Tests at CEA/Saclay



- To simulate the magnetic configuration of TESLA, the possibility of testing the magnet model in the 530-mm aperture of a 2-T MRI magnet (presently in storage at CEA/Saclay) is investigated

New Collaboration with Alstom



- In parallel, discussions are underway with Alstom to develop a new wire with a J_c (non-Cu) of **2000 A/mm²** at 4.2 K and 12 T
- Such wire could be used to build a second quadrupole magnet aimed at achieving **250 T/m at 4.2 K** in a **4 T** background field

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LHC Corrector Magnet List

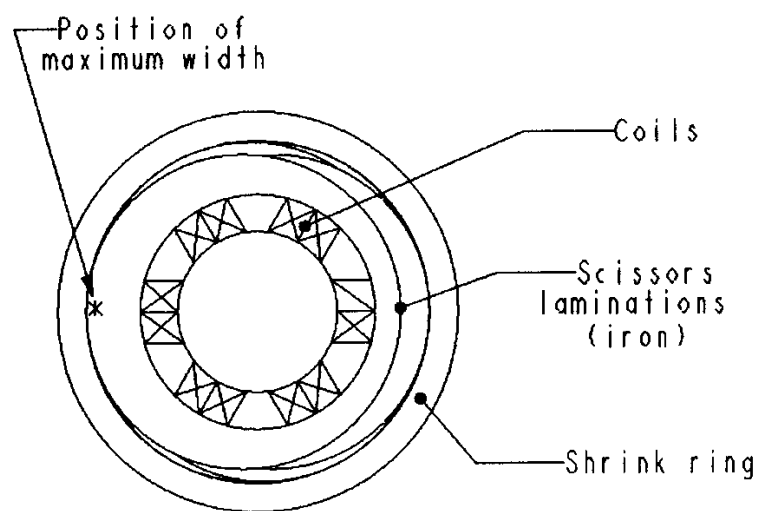
	OVERVIEW OF CORRECTORS 28/1/2000 (parameters are for indication only)						Overvie9.xls						
	For Main Dipole		For Main Quadrupoles				For Dispersion and Insertion Quadrupoles					For Inner Tripl. Quad.	
	Upstream	Downstr.	Upstream		Downstr.		Downstream						
	Decapole	Sextupole	Octupole	Tuning Quad	Sextupole	Dipole	Trim Quad	Dipole	Dipole	Dipole	Wide Dipole	Inner trip Dipole	Inner trip Skew Quad
	MCDO	MCS	MO	MQT/MQS	MS	MCB	MQTL	MCBC	MCBL	MCBR	MCBY	MCBX and Corr.	MQSX and Corr.
Strength S B = S . x^(n-1)	1.2 E6 T/m4 8200 T/m3	1630 T/m2	5.7 E4 T/m3	123 T/m	4430 T/m2	2.9 T	129 T/m	3 T	3 T	2 T at 4.5 K	2.5 T at 4.5 K	3.3 T	30 T/m
Current	550 A / 100 A	550 A	550 A	550 A	550 A	55 A	550 A	100 A	100 A	67 A	100 A	550 A	50 A
Type of Yoke	Single	Single	Twin	Twin	Twin	Twin	Twin	Twin	Twin	Single	Twin	Single	Single
Aperture(s)	58 mm	58 mm	56 mm	56 mm	2 x 56 mm	2 x 56 mm	2 x 56 mm	2 x 56 mm	2 x 56 mm	56 mm	2 x 70 mm	90 mm	90 mm
Outer Diam.Support	115 mm	120 mm	514 mm	514 mm	450 mm	450 mm	450 mm	450 mm	450 mm	185 mm	450 mm	350 mm	350 mm
Magn. Length	66 mm	110 mm	320 mm	320 mm	369 mm	647 mm	1300 mm	840 mm	1250 mm	840 mm	840 mm	500 mm	500 mm
Overall Length	110 mm	160 mm	380 mm	380 mm	465 mm	795 mm	1400 mm	1100 mm	1500 mm	1100 mm	1100 mm	700 mm	700 mm
Approx. weight	6 kg	10 kg	250 kg	250 kg	900 kg in common support		900 kg	800 kg	800 kg	200 kg	800 kg	400 kg	400 kg
Approx. number	1232	2464	168x2	200x2	376x2	376x2	56x2	66x2	12x2	16	36x2	24	8
Design	Cern	Cern	Cern	Accel+Cern	Cern	Cern	Cedex	Cern			RAL	Cern	
Prototype	Cern+CAT	Cern+CAT	Antec+Oswal	Accel+Cern	Tesla	Tesla	Ciemat	Cern			Sigmaphi	Danfysik	

(Courtesy A. Ijspeert)

LHC Corrector Magnet List (Cont.)

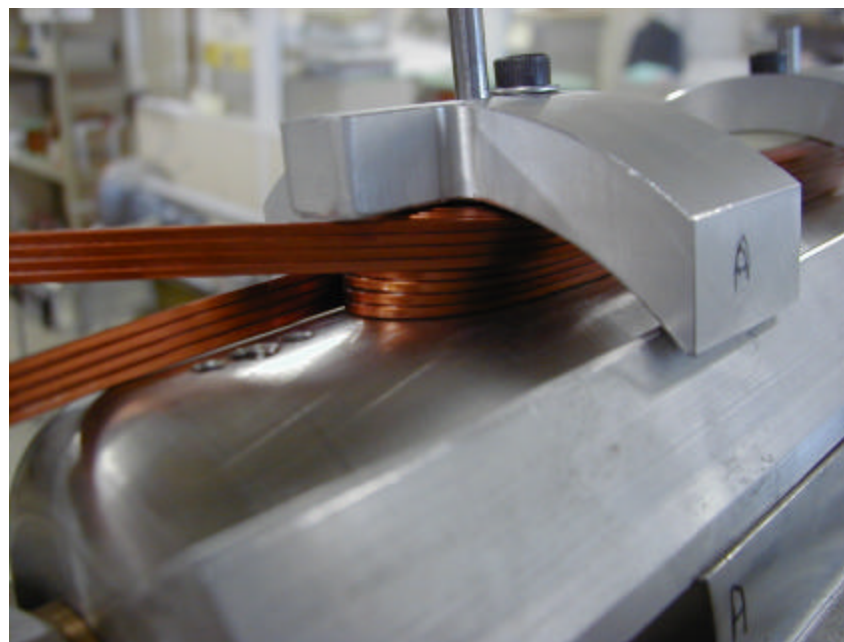
- Most **numerous**: 2464 sextupole and 1232 decapole/octupole correctors for arc dipole magnets
(sextupoles and decapoles are used to correct field distortions due to superconductor magnetization, sextupoles are also used to correct iron saturation effects)
- Most **costly**: 2x376 sextupole and 2x376 dipole correctors for arc quadrupole magnets
(40% of the total cost of all corrector magnets; sextupoles are used for chromaticity corrections and dipoles are used for orbit corrections)
- Most **curious**: 24 nested horizontal and vertical dipole correctors for inner triplets

LHC Corrector Magnet Design Philosophy (after A. Ijspeert)

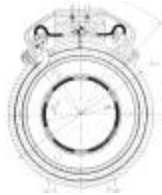


- Tooling is automated to speed-up fabrication (e.g., counter-winding of two layers at same time)

- Most corrector designs are modular and rely on the same concepts (e.g., scissors laminations and shrink ring)



LHC Corrector Magnet Designs

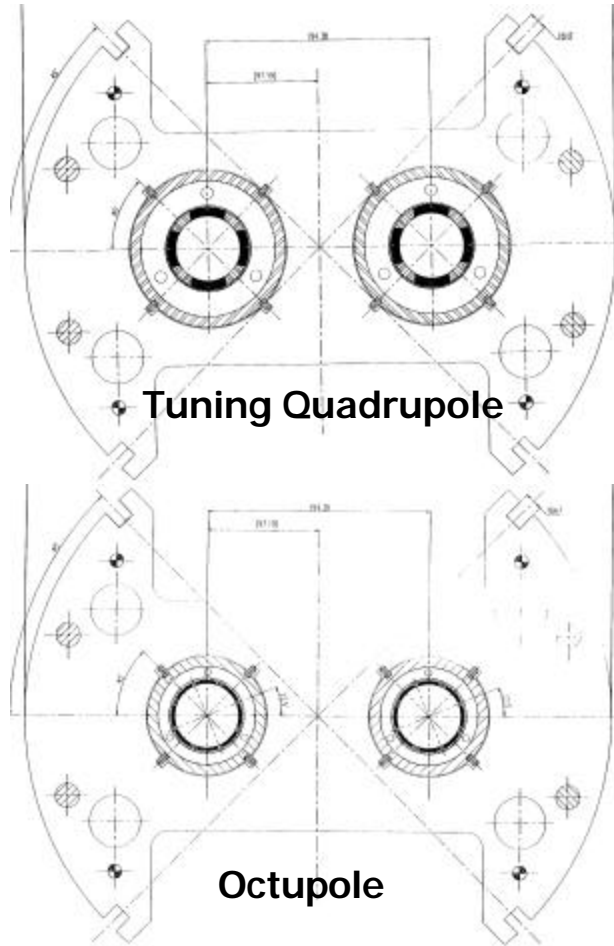


Sextupole



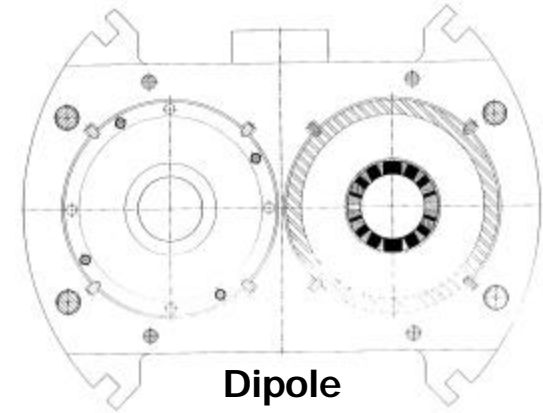
Decapole/Octupole

Arc Dipole

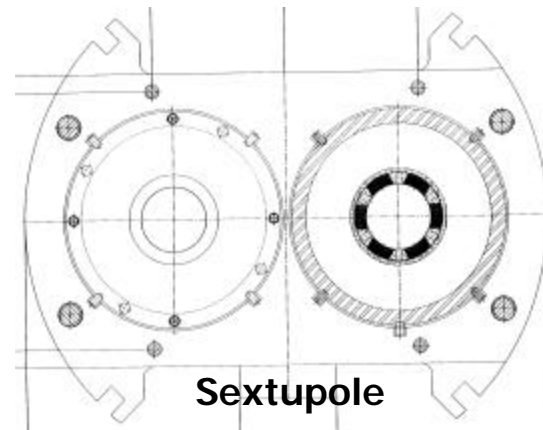


Tuning Quadrupole

Arc Quad. (Upstr.)



Dipole



Sextupole

Arc Quad. (Downstr.)

LHC Corrector Magnet Test Philosophy (after A. Ijspeert)

- Magnetic designs of correctors are such that I_{nom} can be reached at 4.2 K
- All corrector magnets will be measured warm and cold-tested at vendors at 4.2 K
- All pre-series magnets will be cold-tested at CERN + random cold-testing at CERN during production

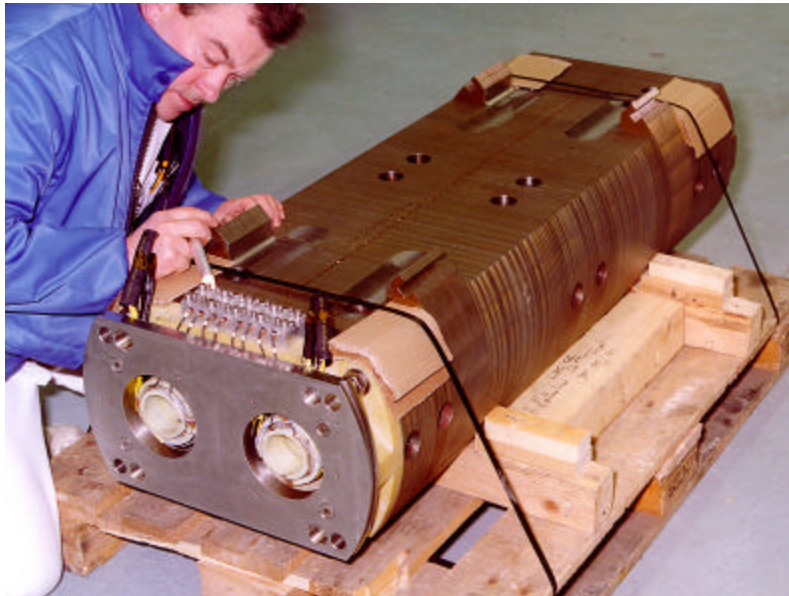
NB: all corrector magnets have one voltage tap and one resistor in parallel for quench protection

Status of Arc Dipole Magnet Correctors

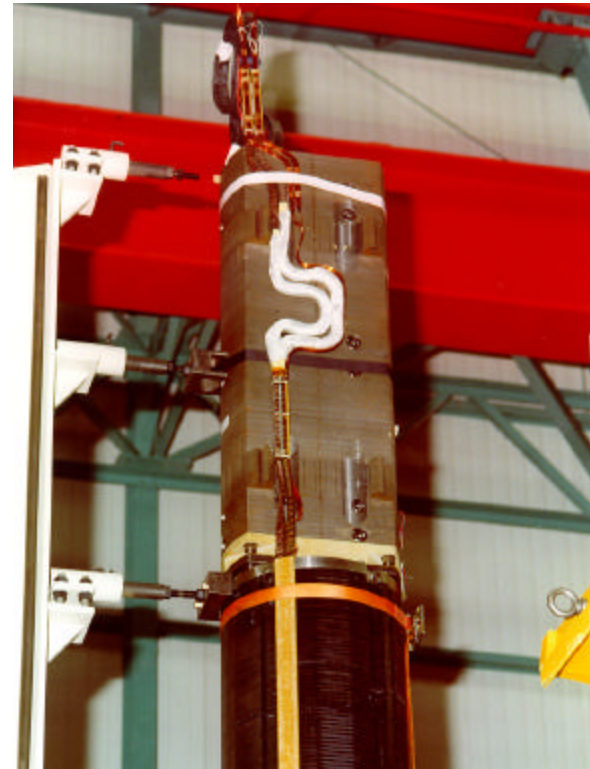
- Half of arc dipole correctors will be provided by India, as part of its special contribution to LHC Magnets are built in industry (Kirloska, located in Bangalore) and tested at the Center for Advanced Technology (CAT, located in Indore)
- Contract for the other half of the sextupole correctors has been awarded to Antec (Spain) and that for the other half of the decapole/octupole correctors has been awarded to Tesla (GB)
- First two sextupole correctors have been delivered to CERN mid-april 2000

Status of Arc Quadrupole Magnet Correctors

- Earlier nested version of dipole/sextupole correctors mounted in the first two SSS prototypes



(Courtesy M. Peyrot)



Status of Arc Quadrupole Magnet Correctors (Cont.)

- In current design, the dipole and sextupole correctors are separated and one prototype of each type has been built and tested



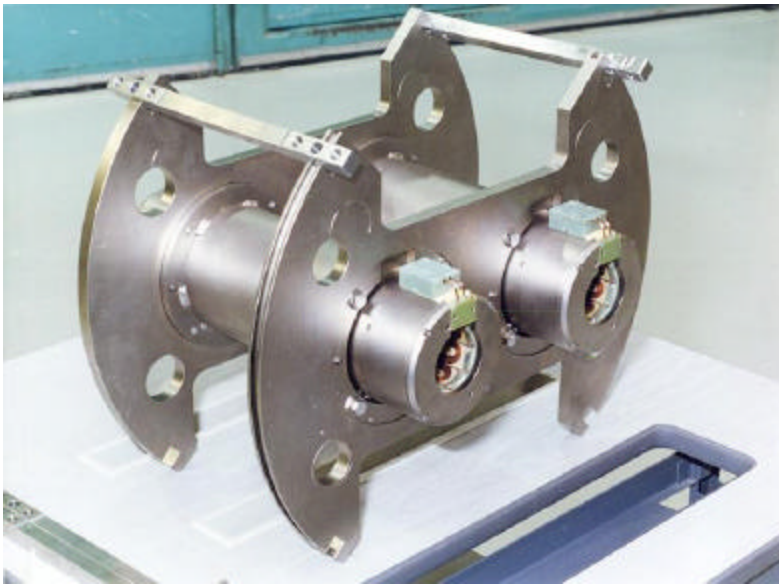
Sextupole Corrector

Dipole Corrector

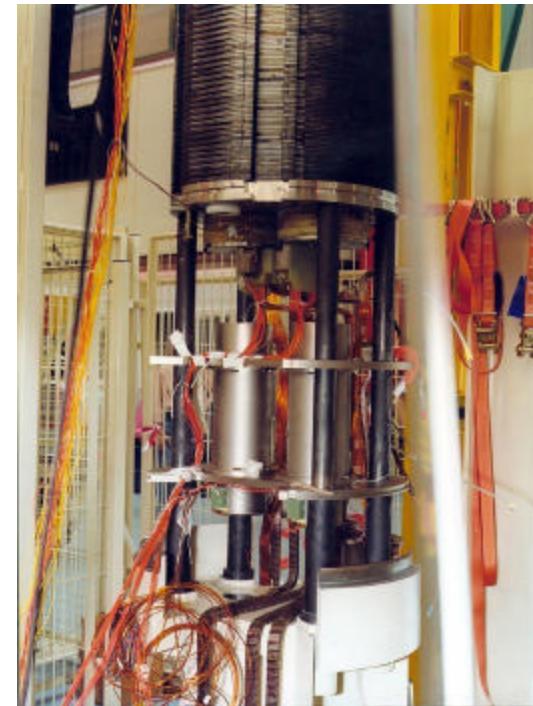
- Contract for the series production has been awarded in March 2000 to one vendor

Status of Arc Quadrupole Magnet Correctors (End)

- First two SSS prototypes also include octupole correctors



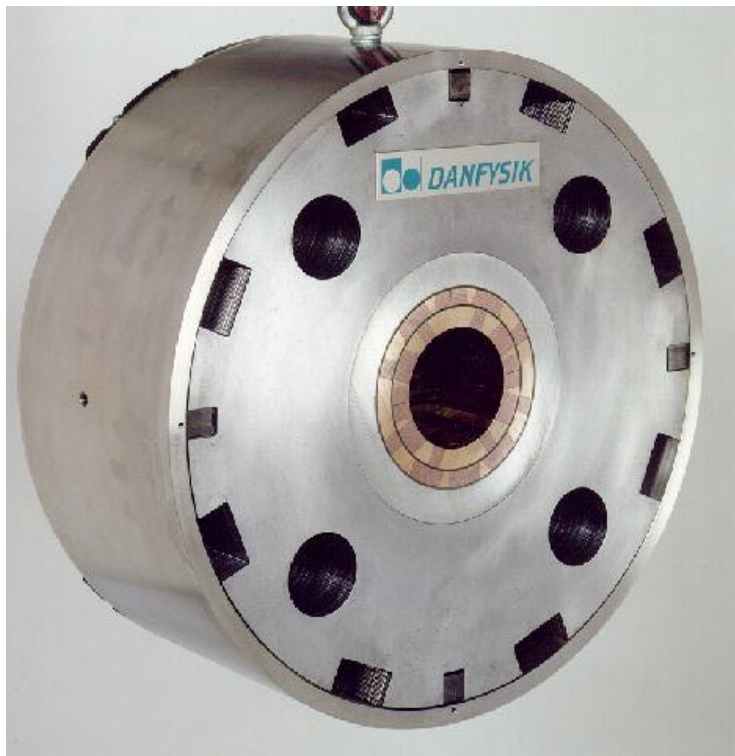
(Courtesy M. Allit)



- Contracts for tuning and skew quadrupole correctors and for octupole correctors to be awarded next June

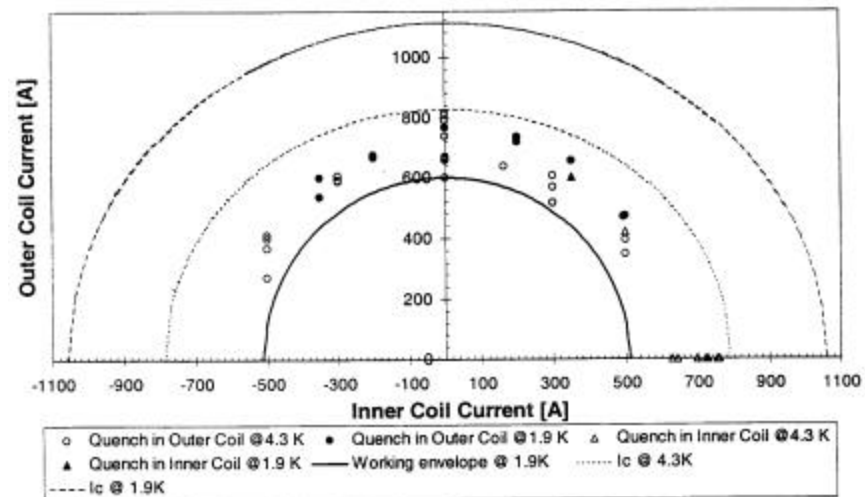
Nested Dipoles for Inner Triplet

- One 90-mm-aperture, 0.6-m-long prototype built at Danfysik and tested at CERN



(Courtesy M. Karpinnen)

- After individual training, combined operation always exceeded **1 Tm**



(Courtesy A. Ijspeert)